REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YYYY)***	**2. REPORT TYPE**	**3. DATES COVERED** ***(From – To)***
12-02-2004	Final Report	25 September 2002 - 25-Sep-03

4. TITLE AND SUBTITLE

~~New Techniques for Minimizing AC Loss in High Temperature Superconductors~~

5a. CONTRACT NUMBER
FA8655-02-1-3067

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5d. TASK NUMBER

5e. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Cambridge
West Cambridge Site
Madingley Rd
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8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EOARD
PSC 802 BOX 14
FPO 09499-0014

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
SPC 02-4067

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

20040715 175

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report results from a contract tasking University of Cambridge as follows: The contractor will investigate:
(a) Measure the AC losses of appropriate Yttrium Barium Copper Oxide (YBCO) samples with strong potential for minimizing losses at high frequencies and magnetic fields with the existing equipment.
(b) Design apparatus which will reproduce the conditions met in lightweight generators and motors, in variable temperatures.
(c) Extend the critical state model for superconductors to include the dependence of critical current density on magnetic field.
(d) Model AC losses of multi-filamentary tapes with filaments connected at their ends by their current leads and determine the effects of filament transposition and/or twisting.
(e) Measure and assess the percolation of electrical super-conducting currents through the narrow YBCO filaments required for minimizing AC loss.
(f) Establish a superconductor processing methodology to minimize AC loss in long lengths of YBCO conductor and model the behavior of the superconductor as part of a complete machine.

15. SUBJECT TERMS
EOARD, Aircraft Subsystem, Power, Superconductivity

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	**17. LIMITATION OF ABSTRACT**	**18, NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
UNCLAS	UNCLAS	UNCLAS	UL	9	MICHAEL KJ MILLIGAN, Lt Col, USAF
					19b. TELEPHONE NUMBER *(Include area code)* +44 (0)20 7514 4955

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39-18

Final Report on EOARD Contract No FA8655-02-1-3067
15 March 2002-1 January 2003.
Extension to AC Loss Minimisation in High Temperature Superconductors

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1. Introduction

During the time of the contract the work proceeded simultaneously on modelling and measuring ac losses, and on designing a new measuring system with a higher magnetic field and frequency. The later was separated out for clarity and was subject of the interim report, so details will not be given here.

In this period of research we have concentrated some effort on a detailed finite element analysis of the measurement aspects of AC losses in coated conductors on magnetic substrates. We analysed different forms of the pick-up coils for AC loss measurements with the objective of finding an optimum solution giving maximum loss signal and minimum inductive voltage.

Later a number of samples from Wright Patterson Airforce base became available, as well as some from Dr.Polak, and a series of AC loss measurements were made on these samples.

We measured AC losses in IBAD and RABiTS non-striated as well as striated coated conductors made by US Air Force Research Laboratory, Wright-Patterson OH. Also samples with different kinds of filament bridging have been measured and their losses compared with those of samples with no filament bridging and with mono-layer samples. This bridging is designed to aid current sharing between filaments which is advantageous, but it is necessary to determine if the effect on AC losses is deleterious.

We have also studied heating and current sharing effects in composite coated conductors. We found a numerical approach which is able to reproduce the whole experimental resistive transition curve by back calculation. It can be used to simulate the properties of different composite materials with input parameters of the individual components taken from experiment. We studied the properties of $YBa_2Cu_3O_{7-x}$ coated conductors deposited onto the non-magnetic ternary alloy NiCrW (RABiTS tape) by in situ pulsed laser deposition.

2. Results

2.1 Coil Performance

First we analysed the properties of a flat pick-up coil suitable for measuring samples in a perpendicular applied magnetic field. We considered a tape sample of rectangular cross-section *a* x *b* and length *l* with a pick-up coil (1 turn) a distance *d* above (or below) the sample surface (Fig. 1, Fig. 2).

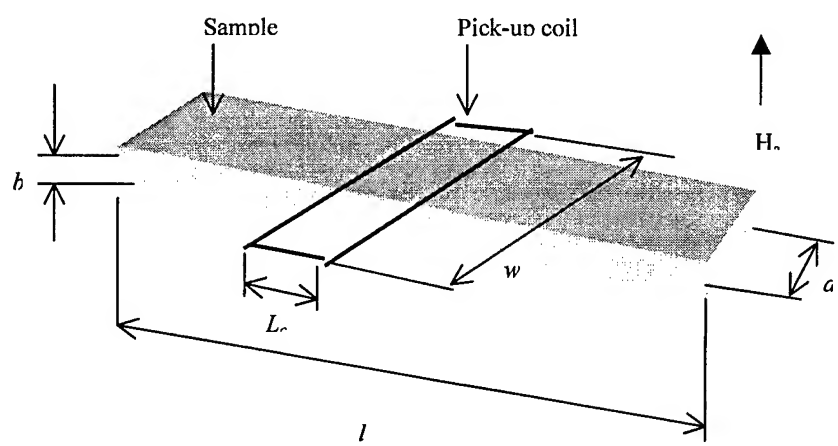


Figure 1. Sample (schematic) and the pick-up coil in the symmetric position (c=0) - a general overview. H_a – applied magnetic field.

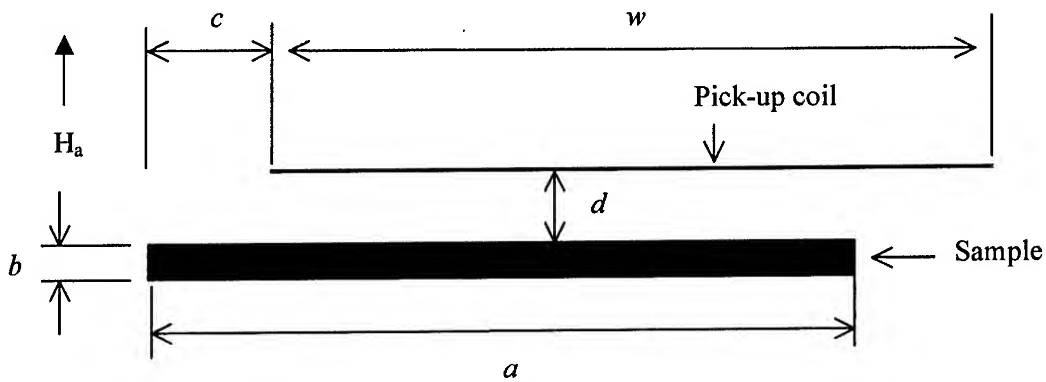


Figure 2. Sample (schematic) and the pick-up coil – a cross-section in a plane perpendicular to the tape length. H_a – applied magnetic field.

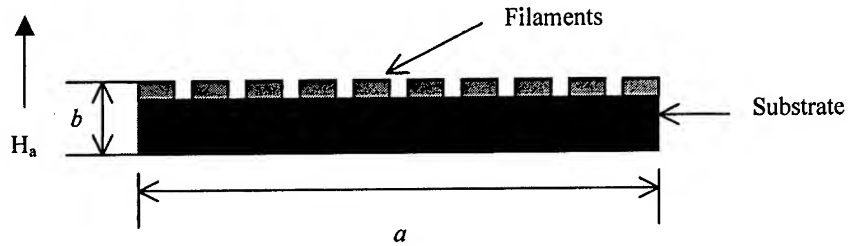


Figure 3. Details of the sample cross-section (schematic – not to scale). Number of filaments 10. Sample width: a=5.9 mm, substrate thickness – 25 μm, filament width – 0.5 mm, filament thickness – 5 μm, separation between the neighboring filaments – 0.1 mm. Sample thickness: b=30 μm. H_a – applied magnetic field.

The width of the pick-up coil was w and its length L_c . It can be positioned with some asymmetry c along the sample width (Fig. 2). Because our interest is in measuring AC losses per 1 meter length of the sample, the condition $L_c << l$ must be fulfilled so that end effects are negligible
With this assumption a 2-dimensional numerical modelling using the finite element method can be used. The sample itself, shown schematically in Figures 1 and 2, had a structure similar to a multifilamentary coated conductor on a metallic substrate. The details of its cross-section are shown in Fig. 3. We set the sample width a=5.9 mm, substrate thickness 25 μm, filament width 0.5 mm, filament thickness 5 μm with the separation between the neighbouring filaments 0.1 mm, which resulted in a sample thickness b=30 μm. We found that a pick-up coil of width equal to the width of the sample gives minimum inductive and maximum loss voltage, but the result is very sensitive to the precise symmetry position with respect to the center of the sample. From this point of view a compromise is a pick-up coil of width 1.7 times the sample width positioned 1.7 times the sample thickness either above the filaments' or below the substrate. The calibration constant is defined as the ratio of the correct losses W, calculated by integration of the dot product $\boldsymbol{E.J}$ through the sample volume, to the losses measured by the pick-up coil and evaluated as $wU_{rms}H_{arms}/f/L_c$. For the dimensions assumed, the calibration constant is 1.44 ± 0.12% with respect to its position either above or below the sample. A lateral shift of 0.1 times the sample width results in an error of <2% in the calibration constant.
Next we analysed the properties of a cylindrical saddle-like coil (Fig. 4), which allows AC loss measurements of the samples at some angle between the tape broader face and the applied magnetic field. The calibration constant does not depend on angle apart from the case where the sample is nearly in a parallel field. In this case the deviation of the calibration constant is 18%. This pick-up coil was built and placed in our measuring apparatus. The measured results on a calibration sample

are shown in Fig. 5. In comparison with the flat pick-up coil of width equal to the width of the sample (Fig.1), the cylindrical saddle-like pick-up coil (Fig. 4) has a ratio of the induced voltage to the loss voltage about one hundred times higher.

As we mentioned in one of our previous reports, it is possible to reduce AC losses by approximately 2 orders of magnitude, without subdivision of the tape into filaments, if the tape is oriented with its face parallel to the applied magnetic field. However measuring the losses in this orientation is very difficult because of the very low level of loss signal in comparison with spurious noise signals. We analysed the geometry of a rectangular saddle-like pick-up coil which gives the highest loss signal in this parallel field orientation. Its geometry is shown in Fig. 6. We have found that the best solution is when the pick-up coil is tightly wound onto the sample and its height is 2 times the sample half width. In this case the calibration constant of the pick-up coil is equal to 1.0221. Making the coil wider decreases the loss signal and increases the inductive voltage.

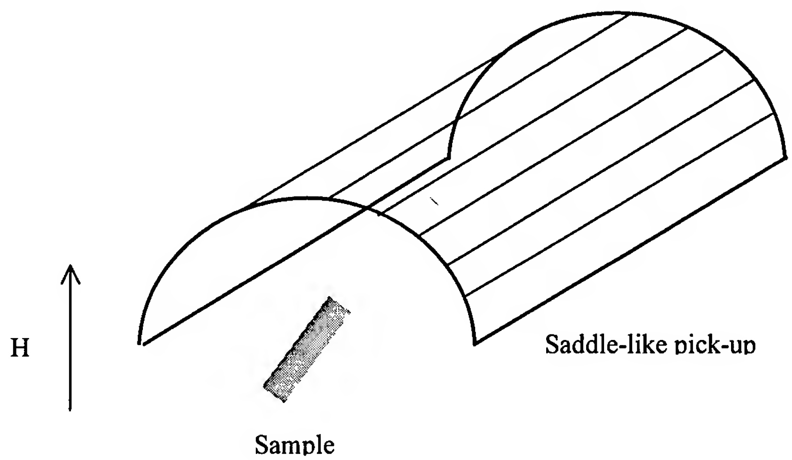


Figure 4. Sample (schematic) and the upper half of the saddle-like pick-up coil. H – applied magnetic field.

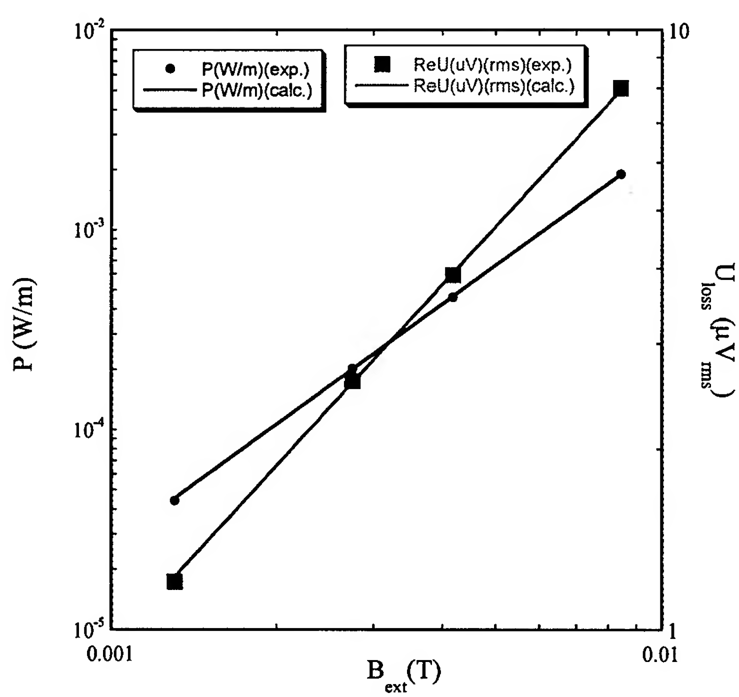


Figure 5. AC loss power and loss voltage of the saddle-like pick-up coil (Fig. 4). Lines – calculated, points – measured on a calibration sample.

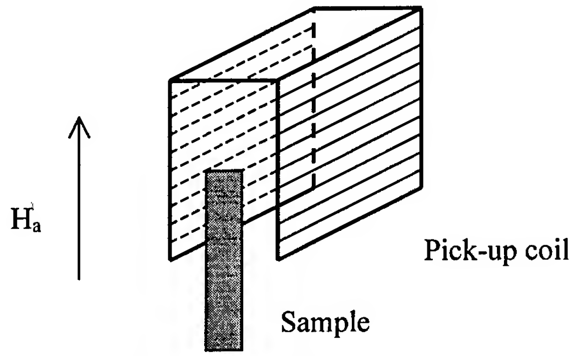


Figure 6. Sample (schematic) and the saddle pick-up coil. H_a – applied magnetic field.

2.2 Critical Current Measurements

We have found that the critical current density of YBCO coated conductors in a perpendicular applied magnetic field follows the Kim dependence on magnetic field quite well. The AC losses show a full penetration behaviour at applied fields higher than about 10 mT. This means that in most practical cases the YBCO coated conductors will work in the fully penetrated state. We have found that in this regime the critical state model, with a $J_c(B)$ dependence according to Kim's relation, originally derived for infinite geometries, can be used also for thin YBCO films. The $J_c(B)$ derived from contactless magnetisation measurements, when inserted into the critical state model equations, gives AC losses in a reasonable agreement with experiment.

2.3 AC Loss measurements

We have measured AC losses at 77.3 K in different kinds of non-striated and striated samples made by the US Air Force Research Laboratory, Wright-Patterson, OH, USA. The measurements have been performed at 3 different frequencies (46.7 Hz, 66.2 Hz and 93.9 Hz,. the number of frequencies is limited by the need to have a different capacitor bank to tune the magnet coil at each frequency). Measurements were also made at different angles α between the applied magnetic field and the normal to the broader face of the tape ($\alpha=0°$, 20°, 40°, 60°, 80°).

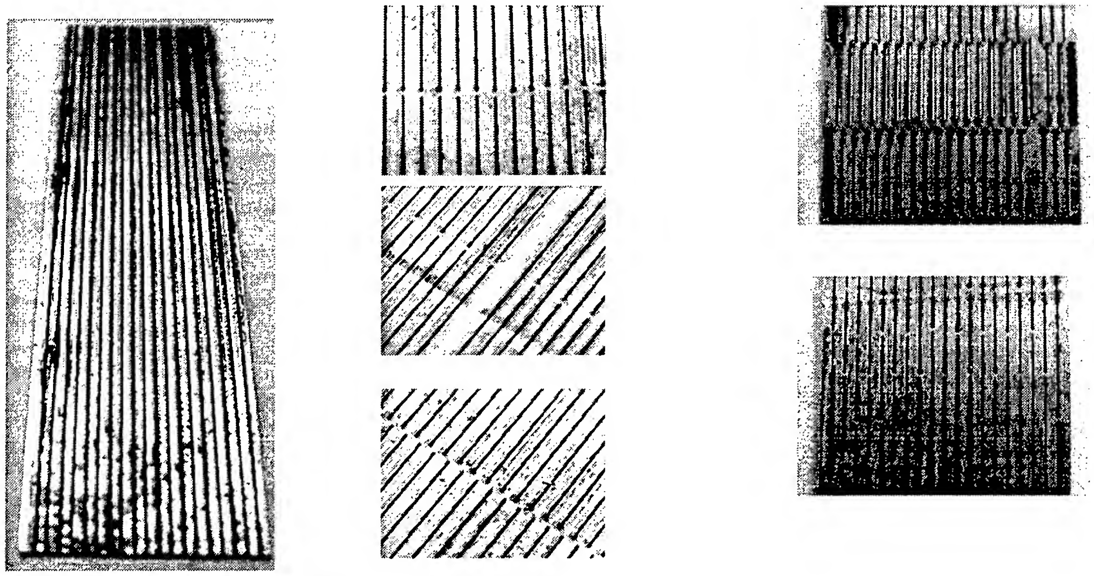
The samples had the following characteristics:-

3 samples were without bridges.
- 1 IBAD monofilament
- 1 RABiTs monofilament
- 1 RABiTs striated multifilament without bridging.

6 bridged samples to assess the effect of current sharing.
- 4 with different types of bridging, one set of bridges per tape.
- 2 with six bridges/ cm i.e. 24 per tape.

1 YBCO on pure Ni to explore the effect of Ni on the loss, (supplied by Dr. Polak).

Pictures of the tapes are in fig 7 and some typical loss measurements in figs 8 and 9.



(a) (b) (c)

Figure 7. a) Striated (20 filaments) sample with no filament bridging, **b)** different kinds of filament bridging – 1 bridge per tape, **c)** different multiple bridges – 6 bridges per cm.

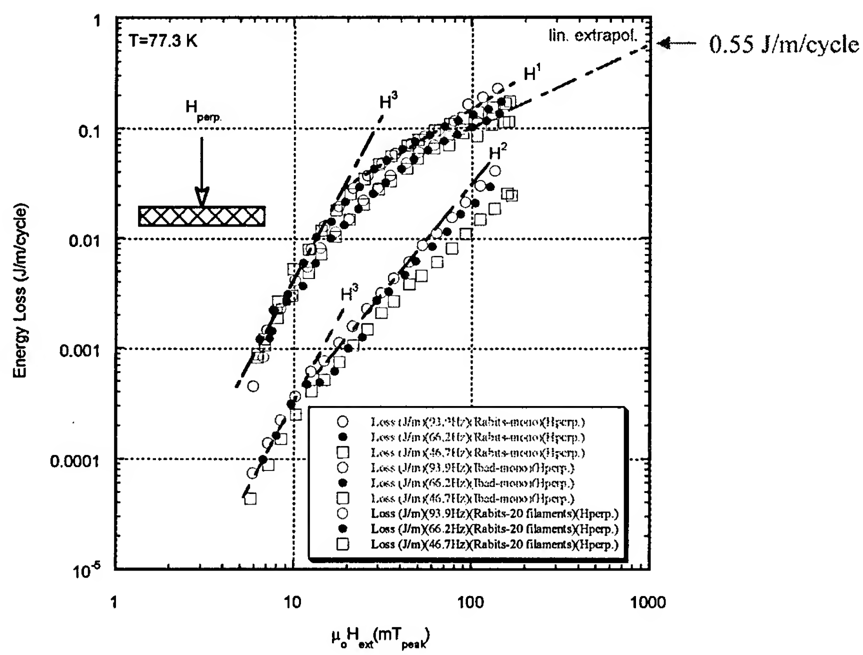


Figure 8. A comparison of AC losses of IBAD sample with RABiTS non-striated and striated (no filament bridges) sample in an applied magnetic field perpendicular to the broader face of the samples.

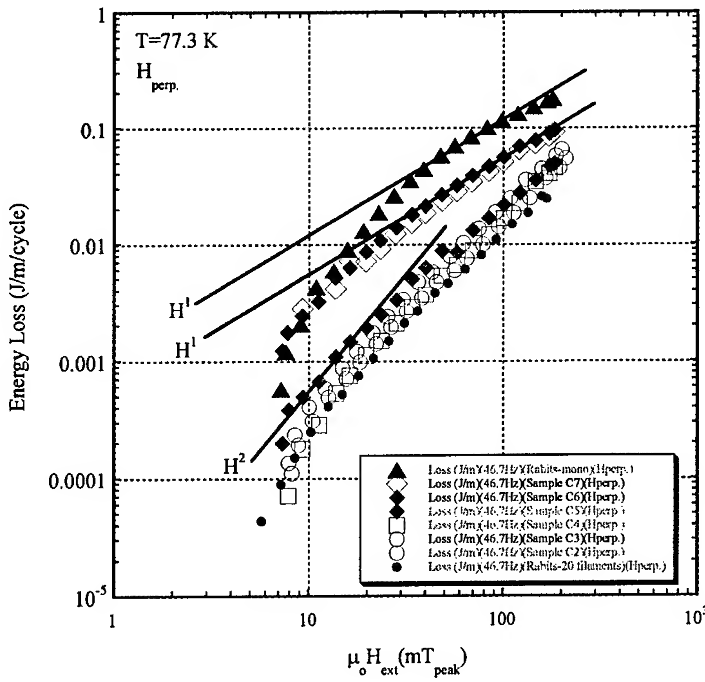


Figure 9. An intercomparison of AC losses of monolayer RABiTS sample with samples having only 1 interfilamentary bridge (Fig. 7b – samples C2 – C5) or multiple bridges (Fig. 7c – samples C6, C7) and with the striated sample with no interfilament bridges (Fig. 7a) in an applied magnetic field perpendicular to the broader face of the samples and at 46.7 Hz.

From the results the following conclusions can be drawn:-

1) For non striated samples the AC losses follow H^3 and H dependencies in accordance with the critical state model (J_c=const) for partial and full penetration regimes, respectively.

2) The frequency dependence of the energy loss per cycle is rather weak

3) The AC losses at different angles are governed mainly by the magnetic field component perpendicular to the broader face of the sample.

4) The IBAD sample has slightly higher losses per unit length than the RABiTS non-striated sample.

5) For RABiTS non-striated sample at fields nearly parallel to its broader face, AC losses in the substrate start to dominate.

6) For the RABiTS non-striated sample in a perpendicular applied magnetic field a linear extrapolation gives a loss value ≈0.55 J/m/cycle at $1T_{peak}$. (This gives ≈220 W/m at 400 Hz and $1T_{peak}$).

7) The RABiTS striated sample has roughly 1 order of magnitude lower losses than the non-striated one confirming the validity of striation in reducing losses.

8) Losses in the RABiTS striated sample are dominated by losses in the substrate at all angles of the applied magnetic field with respect to the broader face of the sample.

9) The presence of a Ni layer in the substrate of RABiTS samples may influence the loss behaviour at higher magnetic fields and different angles due to demagnetizing effects.

10) AC losses of striated samples with only 1 or 2 bridges (Fig. 7b, Samples C2 - C5) are similar to those of the sample with no filament bridging, due to a rather weak filament coupling.

11) AC losses of striated samples with multiple bridges (Fig. 7c, Sample C6, C7) are higher than those of the sample with no bridges due to significant filament coupling but the losses are still substantially lower than those of a monolayer sample. (A similar AC loss increase in Nb_3Sn and BiSrCaCuO-2223 multifilamentary conductors due to superconducting outgrowths which bridged the filaments has also been reported in the literature)

2.3 End Coupling

In a perpendicular field the subdivision of a monolayer tape into filaments leads to an AC loss reduction directly proportional to the number of filaments only when the filaments are decoupled. We pointed out in one of our previous reports that even if the filaments are insulated from each other; this is not the case in practical applications such as power generators, because the filaments are coupled at their ends via the current leads.

In this report we consider the case further for an application in power generators. We propose the conductors for a power generators to be made of two parallel YBCO tapes transposed once in the middle of their length as shown in Fig. 10.

Without the transposition the increase of the losses due to the resistance at the ends depends on the particular geometry and the value of the resistance but it may achieve even one order of magnitude. In the transposed case the increase in the losses is only proportional to the ratio of $\Delta L/L$, where ΔL is the deviation of the position of the point of the transposition with respect to the middle of the conductor. If the point of transposition is exactly in the middle of the conductors (as in Fig. 10), $\Delta L=0$ and so the coupling losses do not exist and the only losses are the hysteretic losses, which in this case are equal to the losses of the tape in a perpendicular field.

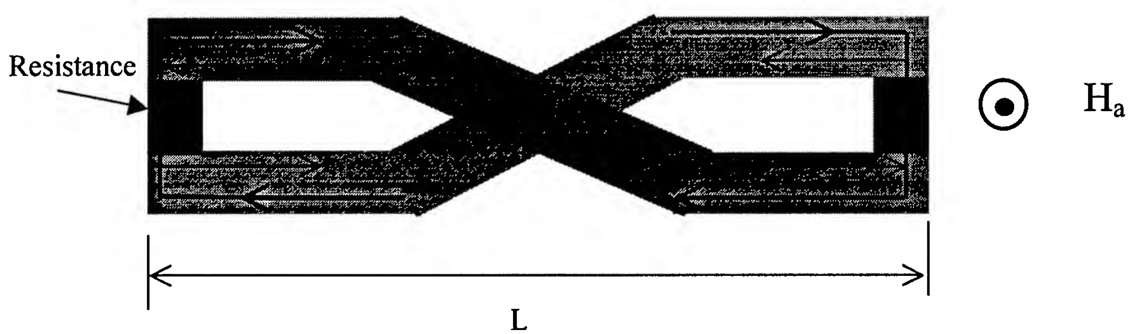


Figure 10. Transposed conductors. H_a – applied magnetic field. The thick arrows show the paths of induced current flow between the tapes and the thin ones those induced in the individual tapes. When $\Delta L=0$ there is no net induced current between the conductors and the currents are induced only in the individual tapes.

If the tape is subdivided into filaments, its hysteresis losses will not be reduced proportionally to the number of the filaments, because the filaments are connected at their ends. The resistive losses in the end connections must be taken into account. Another possibility is to use monofilamentary tapes transposed as shown in Fig. 10, but with the tapes oriented with their face parallel to the magnetic field. In this case the hysteresis losses would be decreased roughly by two orders of magnitude, with respect to the perpendicular orientation, if the tapes were very precisely parallel to the

magnetic field. In this field orientation our simulations show that subdividing the tapes into filaments, even if they were not interconnected by the current leads at their ends, has no significant effect on AC loss reduction.

2.4 Thermal Stability

We have studied numerically by a finite element method the stability of thick YBCO films. It is known that YBCO films have high J_c when they are about 1 μm thick. Increasing their thickness further does not result in increasing their J_c proportionally. Films several micron thick have J_c about an order of magnitude lower than those 1 μm thick. From the point of view of filamentary YBCO tapes with transposed filaments, multilayers will be needed. They will not have such a good orientation as films grown directly onto the substrate, so thick films might be a solution. Roughly, when they are 10 times thicker than the 1 μm films, they will carry the same current. We modelled the stability, the heating and current sharing effects in such films on a NiFe substrate 25 μm thick. We considered the structure YBCO/Ag/NiFe, i.e. a metallic buffer layer which could serve also as a stabilising layer for a current flow. The thickness of YBCO was 10 μm and we modelled different Ag thicknesses in the range 1 μm – 10 μm. We found that a 1 μm thick Ag layer is not sufficient but 5 μm gives good results comparable with those obtained for 1 μm thick films (reported in one of our previous reports).

We extended the analysis further to cover the whole transition curve up to the normal state at room temperature in different cooling media. We found a model, in which the isothermal electrical conductivity of the superconductor was modelled as a sum of the conductivity in superconducting and normal state, to be able to reproduce the whole transition curve. The model uses input data of the individual materials in the composite conductor taken directly from experiment in form of tables and so it allows us to obtain quite realistic results.

2.5 Effect of Substrate Composition

We studied the influence of different substrates – Ni, NiFe, NiCrW – on the quality of YBCO films. Apart from the large grain boundaries, NiO formation along the defects and cracking along the substrate grain boundaries were found as possible current limiting factors. We have demonstrated successful fabrication of well-textured single and double conductive buffer architecture on $Cu_{70}Ni_{30}$ textured tape. Partial substrate oxidation during YBCO deposition appeared to be a problem.

We have developed a computer controlled ink-jet printing technique for coated conductors. This non-vacuum technology allows the formation of complex multi-layer transposed filamentary structures on different substrates. Our first studies show promising results.

2.6 High Field and Frequency Magnets

We explored the possibility of developing a new measuring system of AC losses in coated conductors achieving the same parameters as those met in power generators – namely a magnetic field of 2 Tesla and frequency up to 400 Hz. No such system has been designed previously. We used our experience from our research of AC losses and stability of NbTi fine filamentary superconductors and building ac magnets from them. This was reported in our previous (interim) report and intended as a possible future project if it appears to be necessary and funds are available

3. Future Work

Exchange of information and samples between Wright Patterson, Cambridge, and Dr.Polak is now working well. We will measure losses of samples with new improved structure and properties as they are produced. The details were discussed at the recent AFOSR meeting in St.Petersburg. FL. One thing which became clear at that meeting is that coupling losses are likely to be a major source of loss. We will modify our apparatus to operate at higher frequencies to measure this loss. It may also be necessary to measure longersamples.

List of publications

[1] M. Majoros, R. I. Tomov, B. A. Glowacki, A. M. Campbell, J. Ogawa, O. Tsukamoto, 'AC losses due to ac magnetic fields in $Y_1Ba_2Cu_3O_{7-x}$ coated conductors – the measurement aspects'. Presented at EUCAS'03 conference, Sorrento, Italy, 14-18 September 2003

[2] M. Majoros, R. I. Tomov, B. A. Glowacki, A. M. Campbell, C. E. Oberly, 'Hysteresis losses in YBCO coated conductors on textured metallic substrates'. IEEE Trans. Appl. Supercond. 13 (2003) 3626

[3] M. Majoros, A. M. Campbell, B. A. Glowacki, R. I. Tomov, 'Numerical modeling of heating and current-sharing effects on I-V curves of $Y_1Ba_2Cu_3O_7$ and MgB_2 conductors'. Physica C 401 (2004) 140

[4] R. I. Tomov, A. Kursumovic, M. Majoros, B. A. Glowacki, J. E. Evetts, A. Tuissi, E. Villa, M. Zamboni, Y. Sun, S. Tönies, H. W. Weber, '$Y_1Ba_2Cu_3O_{7-\delta}$ coated conductor deposited onto non-magnetic ternary alloy NiCrW RABiTS tape by in situ pulsed laser deposition'. Physica C 383 (2003) 323

[5] R. I. Tomov, A. Kursumovic, M. Majoros, R. Hühne, B. A. Glowacki, J. E. Evetts, A. Tuissi, E. Villa, S. Tönies, Y. Sun, A. Vostner, H. W. Weber, 'Development of coated conductors on biaxially textured substrates: the influence of substrate parameters'. Ceramic Transactions, 140 (2003) 119

[6] R. I. Tomov, A. Kursumovic, M. Majoros, R. Hühne, B. A. Glowacki, J. E. Evetts, A. Tuissi, E. Villa, 'Coated conductors on $Cu_{70}Ni_{30}$ textured tapes:the potential of a single conductive buffer'. Presented at EUCAS'03 conference, Sorrento, Italy, 14-18 September 2003

[7] B. A. Glowacki, M. Majoros, M. Eisterer, S. Toenies, H. W. Weber, M. Fukutomi, K. Komori, K. Togano, 'MgB_2 superconductors for applications'. Physica C 387 (2003) 153